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RESEARCH PAPER

A basal heat stress test to detect military operational readiness after a 14-day operational heat acclimatization period

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ABSTRACT

A basal heat stress test (HST) to predict the magnitude of adaptive responses during heat acclimatization (HA) would be highly useful for the armed forces. The aim was to identify physiological markers assessed during a HST (three 8-min running sets at 50% of the speed at VO_{2max}) performed just before a 14-day HA period that would identify participants still at "risk" at the end of HA. Individuals that responded poorly (large increases in rectal temperature [T_{rec}] and heart rate [HR]) during the initial HST were more likely to respond favorably to HA (large reductions in T_{rec} and HR). However, they were also more likely to exhibit lower tolerance to HST at D15. Basal T_{rec} was found to efficiently discriminate participants showing a T_{rec} > 38.5°C after HA, who are considered to be "at risk". Finally, participants were classified by quartiles based on basal T_{rec} and HR at the end of the HST and physiological strain index (PSI). Most of the participants "at risk" were among the upper quartile (i.e. the least tolerant) of T_{rec} and PSI (p = 0.011 for both). Overall, these results show that the individuals who are less tolerant to a basal HST are very likely to benefit the most from HA but they also remain less tolerant to heat at the end of HA than those who better tolerated the basal HST. A basal HST could therefore theoretically help the command to select the most-ready personnel in hot conditions while retaining those who are less tolerant.

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Introduction

High inter-individual variability in adaptive responses during heat acclimation [1–4] or acclimatization [5–7] has been highlighted by several studies. The required duration of heat acclimation/acclimatization to reach operational readiness depends on the basal level of heat tolerance and the rate of heat acclimation. Thus, different individuals will not need the same number of days to reach complete adaptation. The ability to confidently predict such individual adaptive responses would be a major improvement for athletes and professionals who may perform mid- to long-term trainings, competitions or missions in areas with a hot climate. For example, athletes would know their optimal number of training sessions in thermal rooms before competition (heat acclimation) or the optimal moment to travel to the place of the competition to initiate heat acclimatization. This individualization would improve compliance with the required heat acclimation, which is surprisingly poor, even for elite athletes [8]. In the armed forces, the command would know which soldiers are likely to tolerate demanding operational missions in the heat (low risk level) and which ones need to temporarily avoid harsh physical activities in the heat (high risk level).

Two methodological approaches to predict heat acclimation and individual risk are possible: 1) constitutive individual biometrics and fitness characteristics and 2) the dynamic response during a heat tolerance or stress test (HTT and HST, respectively). In the first case, it was hypothesized that young [9], lean [10], fit individuals [11,12] and males [13] require less time to acclimate. Studies investigating the second methodological approach are very sparse. Between 1930 and 1940, Dreosti [14–16] was the first and last to use rectal temperature (T_{rec}) at the end of a HTT to assign specific durations of heat acclimation to applicants prior to working in the gold mines of South Africa. Death rates dropped dramatically, supporting the efficacy of this approach. More

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recently, Corbett et al. [2] aimed to predict the adaptive response to heat during a 10-day heat acclimation period using the response to an initial HST. Although they concluded that most of the inter-individual variation of this response remained unaccounted for, certain physiological responses during the initial HST were positively associated with some of the adaptive responses during heat acclimation (e.g. initial end-HST HR with decrease in average HR during HST following heat acclimation and increase in body temperature during initial HST and decrease in the end-HST following heat acclimation). Apart from these studies, the predictability of such adaptive responses has never been evaluated and none have assessed the residual level of risk at the end of the heat acclimation period.

A 14-day operational heat acclimatization (~40°C and ~20% of relative humidity) period experienced by 47 French soldiers was used to identify whether individual characteristics and/or markers among the psycho-physiological metrics assessed during an initial HST were related to the amplitude of adaptive responses and could predict the residual level of risk for heat injuries at the end of the heat acclimatization period. Changes in T_{rec} and heart rate (HR) at the end of the HST, the increase of T_{rec} and HR during the HST, and sweat loss were used as the main markers of the adaptive response during heat acclimatization [2]. In addition changes in physiological strain index (PSI) [17] were calculated as it combines the T_{rec} and HR responses.

Materials and methods

Participants

Results obtained during a previous study [18] were used for the analysis during which 47 French soldiers were acclimatized over 14 days (see characteristics in Table 1). All participants were recruited among the same regiment. Although they were separated into several sub-units (n = 12), their schedules were strictly identical. Thus, the volume and intensity of operational physical activities were not self-determined but imposed by the command and similar for all participants. The risk that adaptive responses were influenced by different physical loads was therefore theoretically null. Participants were briefed before leaving France and informed of the benefits and risks of the investigation prior to giving their written consent, in accordance with the Declaration of Helsinki. This study was performed at the request of the French Armed Forces in the United Arab Emirates and approved by the scientific leadership of the French Armed Forces Biomedical Research Institute. All participants were found to be healthy by military physicians. The participants did not participate in a mission (in France or elsewhere) where the climate could be considered to be hot (dry or humid) during the previous six months, and thus could not be considered as acclimated, as a three-month period is generally considered to allow complete decay of the effect [1]. The fitness level was assessed using the Cooper 12-min run test [19] (a test routinely used by the French Army) performed in the month before departure to the United Arab Emirates in a temperate environment (15–20°C). This test is considered one of the most accurate field tests to determine aerobic fitness [20].

Table 1. Participant characteristics.

	Means ± SD
Age (years)	23.9 ± 3.7
Height (cm)	177 ± 6
Body mass (kg)	74.5 ± 9.8
Body mass index (kg.m^{-2})	23.7 ± 2.7
Body surface area (m2)	1.91 ± 0.1
Cooper performance (m)	2871 ± 159
Estimated VO_{2max} (ml.min^{-1}.kg^{-1})	52.9 ± 3.6
Estimated speed at VO_{2max} (km.h^{-1})	15.1 ± 1.0
Running speed during heat stress test (km.h^{-1})	7.6 ± 0.5

Procedure

The protocol is presented in Figure 1. The participants performed a HST (three 8-min runs, outdoors, at 50% of their estimated speed at maximal oxygen uptake; VO_{2max}) one day after their arrival (D0) and after heat acclimatization (D15). The HST was designed as such for the following reasons: 1) it was sufficient to highly induce thermoregulatory mechanisms, allowing us to observe differences between participants, 2) it was sufficiently short to not endanger the participants and prevent heat illness, and 3) it was intermittent to allow medical staff to check the medical state of the participants. Indeed, the medical staff reported numerous previous cases of physical efforts that led to multiple and concomitant heat illnesses of heat-acclimatized soldiers under the same

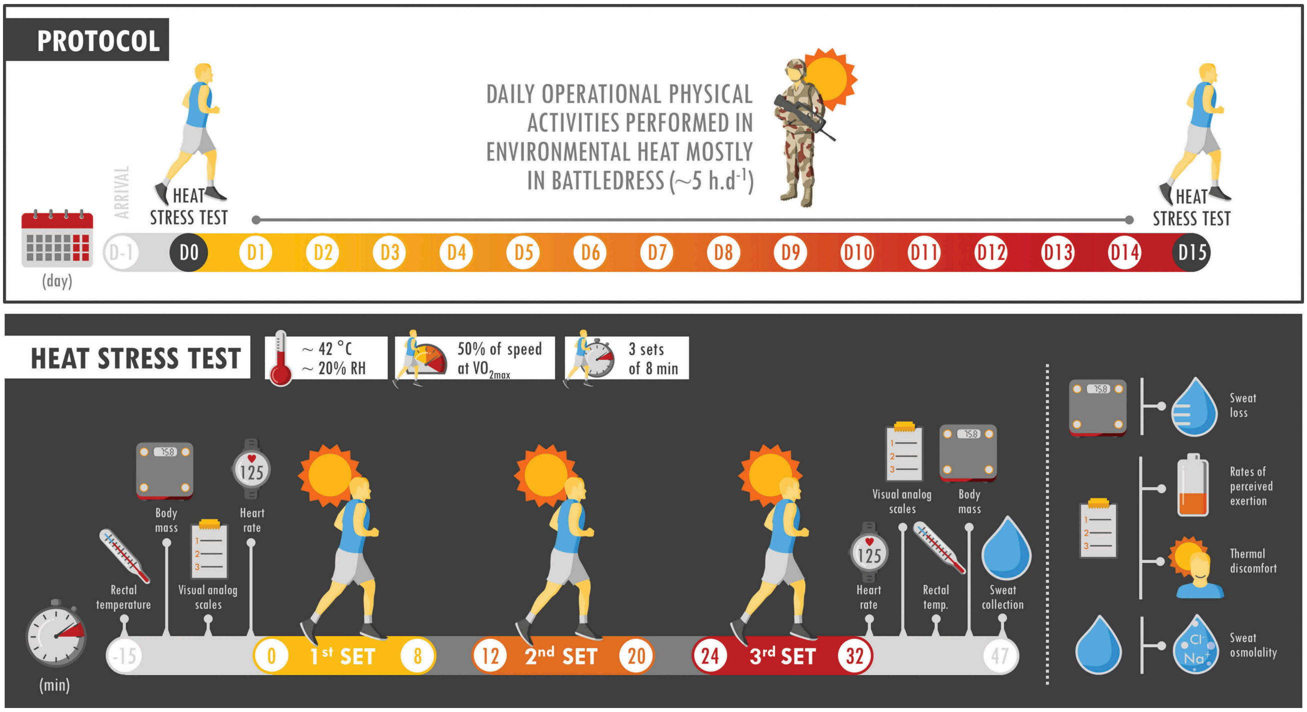

Figure 1. Description of the protocol. 1) Participants performed a heat stress test one day after arrival (D0) and after 14 days of heat acclimatization (D15). From D0 to D15, all participants performed military tasks, mostly outdoors. These activities were not controlled. 2) The HST test consisted of three 8-min periods of running at 50% of the speed at VO_{2max} with 4-min recovery periods in between. Rectal temperature, nude and dry body mass, heart rate, and thermal discomfort were assessed before and at the end of the HST test. At the end of the tests, perceived exertion was determined and the sweat was recovered from sweat collectors for sweat osmolality measurements.

environmental conditions. The aim was thus to avoid inducing medical complications in personnel who were at the base for their military mission.

Given the large sample, it was not possible to perform the test at the same time for all participants. The test was therefore divided into four sessions (12–14 participants per session: two in the morning and two in the afternoon). Participants performed the HST in the same session order for each HST to minimize environmental and, especially, chronobiological differences between the tests. Participants entered a room located near the outdoor track, at least 1 h after breakfast or lunch, to be equipped (HR monitor and sweat collector on the chest) and several measurements were performed (body mass [BM] and T_{rec}). The air-conditioning was turned off (T ~ 30° C) to limit the temperature gradient between the inside and outside. Thermal discomfort (TD) was assessed about 5 minutes before starting the test outside in the shade.

The running track consisted of a 15-m wide and 250-m long loop on an asphalt road. The intensity was fixed at 50% of the estimated speed at VO_{2max} and participants had to run three times for 8 min with 4 min of active recovery in between (walk from 3 to 5 km.h^{-1}). Participants were grouped by fitness level for each session (no more than four groups per session). Colored cones (one color for each level) were placed along the track. A military instructor whistled every 20 s and participants had to reach the next cone by this signal. The distances between the cones were calculated to impose a speed corresponding to the desired intensity. The cones were placed such that each 8-min set finished at the same place for all group levels to facilitate post-exercise measurements. No participant failed to respect the running speed.

At the end of exercise, following completion of the TD and rates of perceived exertion (RPE) scales, the HR monitors were removed. The participants then returned to the first room to measure their T_{rec} (post-HST T_{rec} was measured no more than five minutes after the end of exercise). The sweat collectors were then removed after sweat collection and the nude BM measured no more than 15 min after the end of exercise.

Environmental conditions were measured from the beginning to the end of each test with a weather meter (Kestrel Meter 440 Heat Stress Meter, Birmingham, MI, USA) near the track at a height of 1.2 m and exposed directly to the sun. At least three measurements were performed. The mean of each component was then calculated: wind speed and dry-bulb, wet-bulb, globe thermometer, and wet-bulb globe (WBGT) temperatures. These conditions were similar before and after heat acclimatization (dry-bulb temperatures: 43.2 ± 4.5 and 43.3 ± 4.2°C at D0 and D15, respectively; wet-bulb temperature: 29.1 ± 0.9 and 28.3 ± 1.3°C at D0 and D15, respectively; globe thermometer temperature: 56.3 ± 3.9 and 57.1 ± 3.4°C at D0 and D15, respectively, and WBGT temperature: 35.9 ± 0.7 and 35.4 ± 0.3°C at D0 and D15, respectively).

During the heat acclimatization period, all participants were operational and spent several hours performing military tasks outdoors (~5 $h.d^{-1}$ [18]). Half of participants performed an additional daily training program (3 to 5 sets at 50–60% of VO_{2max}). As no difference was found between the experimental and the control groups in the adaptive response in T_{rec}, HR and therefore PSI during HST [18], the data for all participants were merged.

Measurements

T_{rec} were measured by the participants themselves with electric thermometers (PX-TH 418, Pelimex, Ingwiller, France) at a depth of 6 cm. Recent studies have suggested that measurements of this depth are concordant with deeper measurements [21,22]. Participants were equipped with a chest belt and a HR monitor wrist receptor (RC3 GPS, Polar, Kempele, Finland). Resting HR was measured just before the HST in an upright position, without moving, for 5 min (the lowest 1-min plateau was used for the mean calculation). The HR at the end of exercise corresponded to the mean of the last 30 s of the final 8-min run. The PSI [17] to assess the physiological response to exercise performed in the heat was then calculated ($PSI = 5(T_{recf\,-}\,Tre_0)(39.5 - T_{rec0})^{-1} + 5(HR_f - HR_0)(180 - HR_0)^{-1}$; where T_{rec} is the T_{rec}, f at the end of exercise and 0 before exercise). PSI has been shown to be a reliable indicator of heat intolerance [23]. The thermal-circulatory ratio (TCR; $T_{recf}.HR_f^{-1}$) was also calculated [24]. This ratio is also considered to be a good index to evaluate heat intolerance. The sweat loss was calculated by subtracting the nude dry BM measured before and after the HST with a balance (Mett ler Toledo ICS 425d, Greifensee, Switzerland, accurate to 20 g). Sweat was collected using a self-made impermeable sweat collector placed on the chest and stored in 2-ml aliquots. The collector consisted of a 10-cm plastic square held against the skin with a large transparent film dressing (15 x 20 cm; Tegaderm 1628, 3 M, Neuss, Germany). Sweat was thus retained in this square during exercise and could not evaporate. Immediately after collection, osmolality was assessed using a freezing point osmometer (Osmomat 3000 basic, Gonotec, Berlin, Germany).

For TD, participants had to answer the question "How do you find the thermal environment?" by placing a horizontal dash on a vertical 10-cm scale in which the bottom extremity represented "comfortable" and the top extremity "very uncomfortable". The distance in centimeters between the lower extremity and the line gives the TD score. This scale was adapted from a previous study [25] and translated into French. Rates of perceived exertion were assessed using a 0 to 10 scale [26]. The PeSI [27] was calculated to obtain a single perceptual marker ($PeSI = 5(TD_f.100^{-1}) + 5(RPE.10^{-1})$; where TD_f is TD at the end of exercise).

Statistical analyses

A four step analysis was performed. First, after ensuring that the data were normally distributed using a Shapiro-Wilk test, Student *t* tests were performed to assess the effect of heat acclimatization on the psychophysiological markers measured during HST at D0 and D15.

Second, Pearson's correlation coefficients between the participant characteristics (age, BM, body surface area [BSA], BSA/BM, Cooper performance, VO_{2max}, and running speed), psycho-physiological responses to the initial HST (sweat loss and osmolality, T_{rec} and HR at rest, at the end of the HST, and the change within HST; PSI, TCR, and TD at rest and at the end of the HST, RPE, and PeSI) and five markers of the adaptive response during heat acclimatization (T_{rec} and HR at the end of HST, the increase in T_{rec} and HR during the HST, and PSI) were calculated. This process was performed twice, first using the absolute values obtained during the HST at D15 and then using the amplitude of the differences between D15 and D0. Since the amount and rate of sweat loss did not increase during heat acclimatization in this study (see part 3.1.), it was not included it as a classical marker of the adaptive response.

Third, two analyses were used to assess the ability of the main basal physiological markers to identify still "at risk" individuals at the end of acclimatization. A threshold value of 38.5°C of T_{rec} has been used to characterize heat-intolerant individuals [28,29]. It was used to discriminate between "safe" and "at risk" individuals. First, a receiver operating characteristic (ROC) analysis for each of the main basal markers (T_{rec} and HR at the end of the HST, the increase in T_{rec} and HR during the HST, and PSI) was performed. The area under the ROC curve (AUC) represents the accuracy of the basal marker for identifying participants "at risk" better than chance. An area of 1 represents a perfect prediction; an area of 0.5 represents a random prediction [30]. Then, the relationships between these main basal markers and T_{rec} at the end of the HST at D15 were explored. Participants were separated into four quartiles based on each of the markers at D0. The proportion of participants still "at risk" at D15 was compared by a Chi-square test (χ^2) to know whether these markers at D0 were pertinent for detecting individuals still "at risk" at the end of acclimatization.

Data in the text are presented as the means ± standard deviation (SD). Significance was defined as $p < 0.05$. Analyses were performed using SPSS software (v20, IBM SPSS Statistics, Chicago, IL, USA). Some sweat collectors deteriorated during the HST. Thus, the measurements for sweat osmolality were obtained for 30 participants only.

Results

Heat acclimatization-induced modifications

The heat acclimatization-induced modifications have already been presented in a previous article with the same sample [18]. Briefly, T_{rec} at the end of exercise (−0.55 ± 0.45°C, $p < 0.001$), but not at rest (−0.11 ± 0.46°C, $p = 0.104$), was reduced by heat acclimatization. The increase in T_{rec} during the HST also decreased (−0.44 ± 0.51°C, $p < 0.001$). The HR at rest (−8 ± 12 bpm), at the end of exercise (−19 ± 11 bpm), and the increase in HR during the HST (−11 ± 12 bpm) were all reduced by heat acclimatization. The PSI (−2.08 ± 1.21) and TCR (0.027 ± 0.017°C.bpm^{-1}) were also improved at D15 relative to D0 ($p < 0.001$ for both). Sweat loss (−0.13 ± 0.12 l) and osmolality (−21 ± 31 mOsmol.l^{-1}) were reduced by heat acclimatization ($p < 0.001$ for both). Individual responses for the main markers of heat acclimatization at D15 (T_{rec} and HR at the end of the HST and the change within HST, PSI, and sweat loss) are shown in Figure 2. Rankings were very different between markers, indicating that individuals may adapt non-similarly. For example, one individual may adapt well for T_{rec} but poorly for HR or sweat loss.

There was also a reduction in TD at the end of exercise (−19 ± 23 mm, $p < 0.001$) but not at rest (−5 ± 22 mm, $p = 0.191$), the RPE (−2.3 ± 1.6, $p < 0.001$), and the PeSI (−2.12 ± 1.06, $p < 0.001$) after heat acclimatization.

Correlations between basal responses to HST and adaptive responses

Correlation coefficients between the thermoregulatory responses during the HST at D15 and the participants' characteristics and thermoregulatory responses during the HST at D0 (Figure 3(a–e)) were first calculated. As sweat loss did not increase during heat acclimatization in this study, it was excluded from the main markers of adaptive responses.

Changes in T_{rec} during the HST at D15 positively correlated with changes in T_{rec} during the HST at D0 (Figure 3(a,b)). Similarly, the HR at the end of the HST at D15 and the increase in HR during the HST at D15 positively correlated with HR measurements assessed at D0 (HR at rest and at the end of the HST and the increase in HR during the HST; Figure 3(c, d)). Moreover T_{rec} at the end of the HST at D0 was also associated with the HR at the end of the HST at D15. Interestingly, the PSI at D15 correlated with most of the physiological responses assessed during the HST at D0 (T_{rec} at the end of the HST, all HR measurements, PSI, and TCR) and all subjective markers (TD at the end of the HST, the RPE, and PeSI), with the exception of TD at rest (Figure 3(e)). The thermoregulatory responses at D15 correlated far more with the responses to the initial HST at D0 than with the participant's characteristics. Overall,

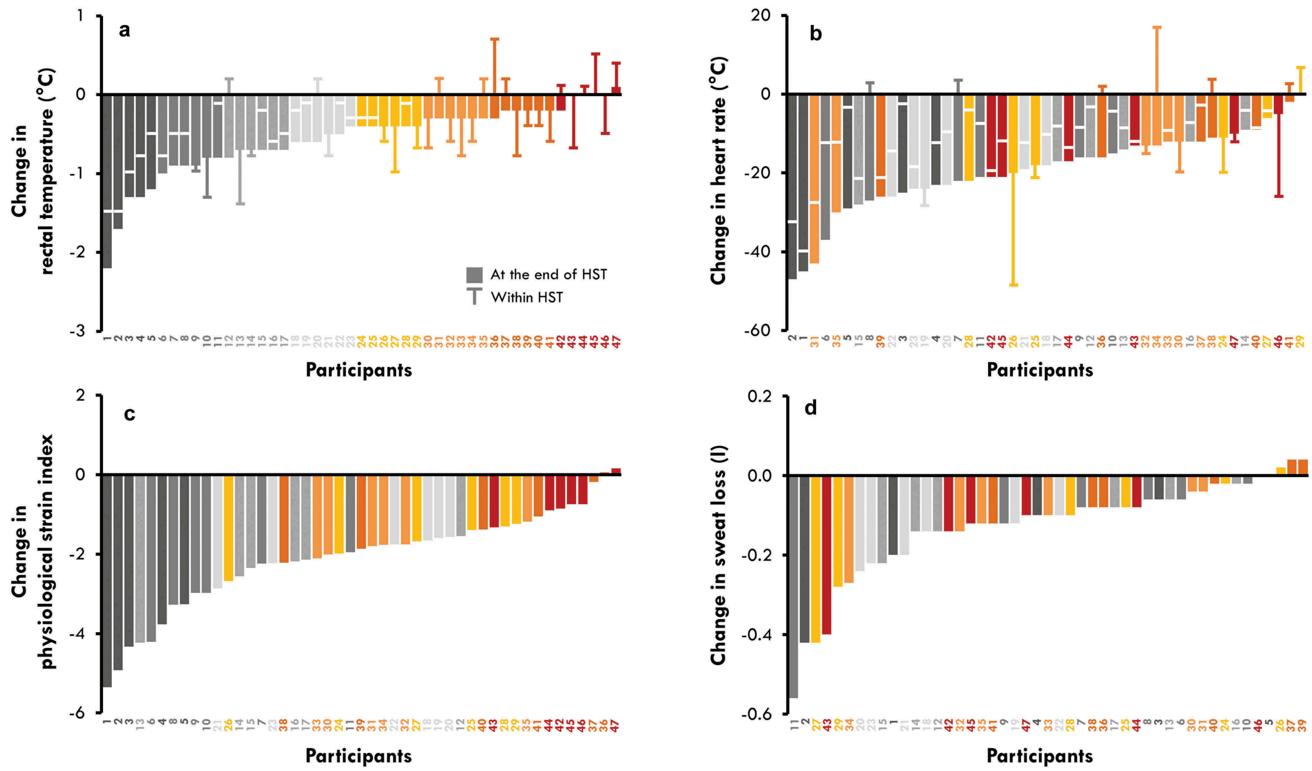

Figure 2. Individual adaptive responses for the major markers of heat acclimatization: rectal temperature (T_{rec}, a), heart rate (b), physiological strain index (PSI, c), and sweat loss (d). The number of each participant was based on the ascending order rank for rectal temperature at the end of HST. A shaded color code was used to visually highlight the difference in adaptive responses between markers.

this shows that the higher the thermoregulatory responses are at D0, the higher they are at D15. In other words, individuals less tolerant to the HST at D0 will retain this status during the HST at D15.

The second level of analysis assessed how the amplitude of the adaptative responses to the HST during heat acclimatization (D15 *vs* D0) correlates with the participants' characteristics and thermoregulatory responses during the HST at D0 (figure 3(f–j)). The significant correlations were mostly restricted to the same marker. Thus, the adaptive response of T_{rec} was negatively associated with T_{rec} markers at D0 (figure 3(f,g)). The same was true for HR (Figure 3 (h,i)). Again, improvements in the PSI during heat acclimatization correlated better with almost all T_{rec} and HR responses to the HST at D0 (Figure 3(j)).

Detection of still "at risk" individuals at D15

Taking into account the importance of the physiological responses during the initial HST, ROC curves (Figure 4) were performed for each factor (HR and T_{rec} at the end of the HST, the increases in T_{rec} and HR during the HST, and PSI at D0) to identifiy "at risk" and "safe" participants during the HST at D15. Areas under the curves of the risk score model in predicting "at risk" individuals at the end of heat acclimatization were ranked as good (0.8–0.9) for T_{rec} at the end of the HST (0.857), as well as the PSI (0.822). The AUC for HR was judged as fair (0.740). Absolute values at the end of the HST were more pertinent than the change within HST. The three absolute markers were therefore conserved for the following analysis.

The correlations between the three remaining main markers (T_{rec} and HR at the end of the HST and PSI at D0) and T_{rec} at the end of the HST at D15 were explored and the number of participants "at risk" in each quartile (Figure 5) compared. The repartition was unequal for T_{rec} at the end of the HST and PSI (p = 0.011 for both). More participants still "at risk" at the end of acclimatization were in the upper quartiles.

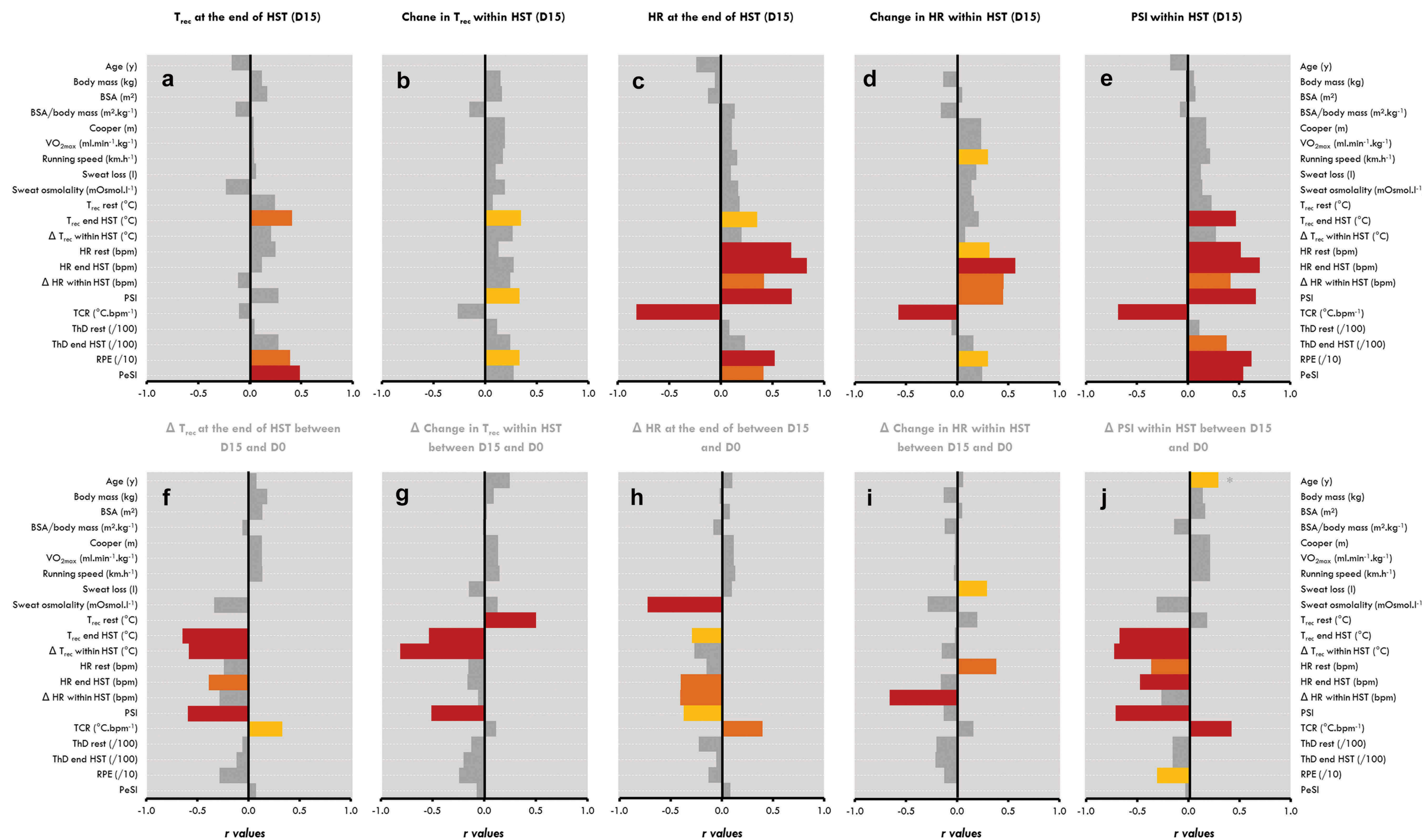

Figure 3. Correlation coefficients for associations between thermoregulatory responses within HST at D15 (a–e) or adaptive responses at the end of heat acclimatization (f–j) and participants' characteristics and thermoregulatory responses during the HST at D0. Red bars: $p < 0.001$, orange bars: $p < 0.01$, yellow bars: $p < 0.05$.

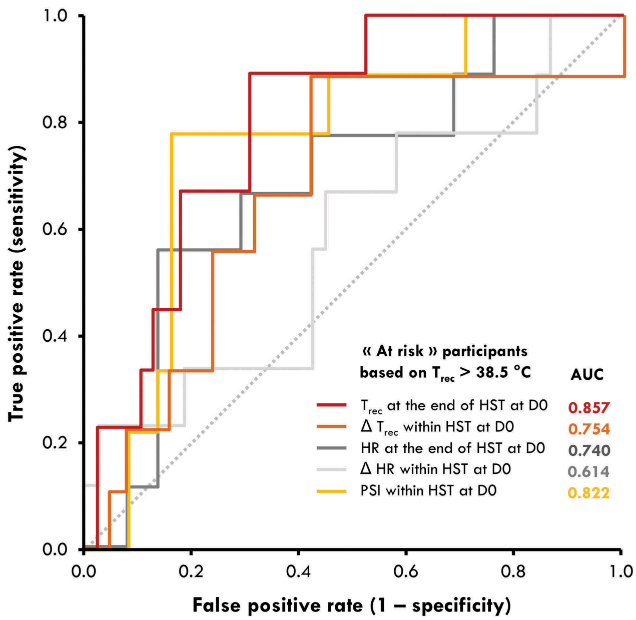

Figure 4. Receiver operating curve (ROC) analysis risk score for predicting individuals at risk (T_{rec} > 38.5°C) based on basal markers.

Discussion

Within the context of a 14-day heat acclimatization period, consisting of ~5 h.d^{-1} of outdoor military physical activities in a very hot and dry environment, the various analyses performed in this study broadly show that: 1) anthropometrical measurements and fitness level are not directly associated with adaptive responses, 2) individuals that are less tolerant to an initial HST tend to be those that have the largest adaptive responses, 3) these same individuals also tend to be those that are still the least tolerant to HST after heat acclimatization, indicating that 14 days of heat acclimatization are not sufficient to allow them to reach the same level of heat tolerance as the individuals who were the most thermotolerant to the initial HST, and 4) individuals "at risk" at the end of heat acclimatization can be easily and fairly accurately predicted by basal (at D0) T_{rec} at the end of the intial HST and the PSI.

Variability in adaptation during heat acclimatization

Inter-individual variation in the acute response to a single HST and in the adaptive response during heat acclimation/acclimatization was very large

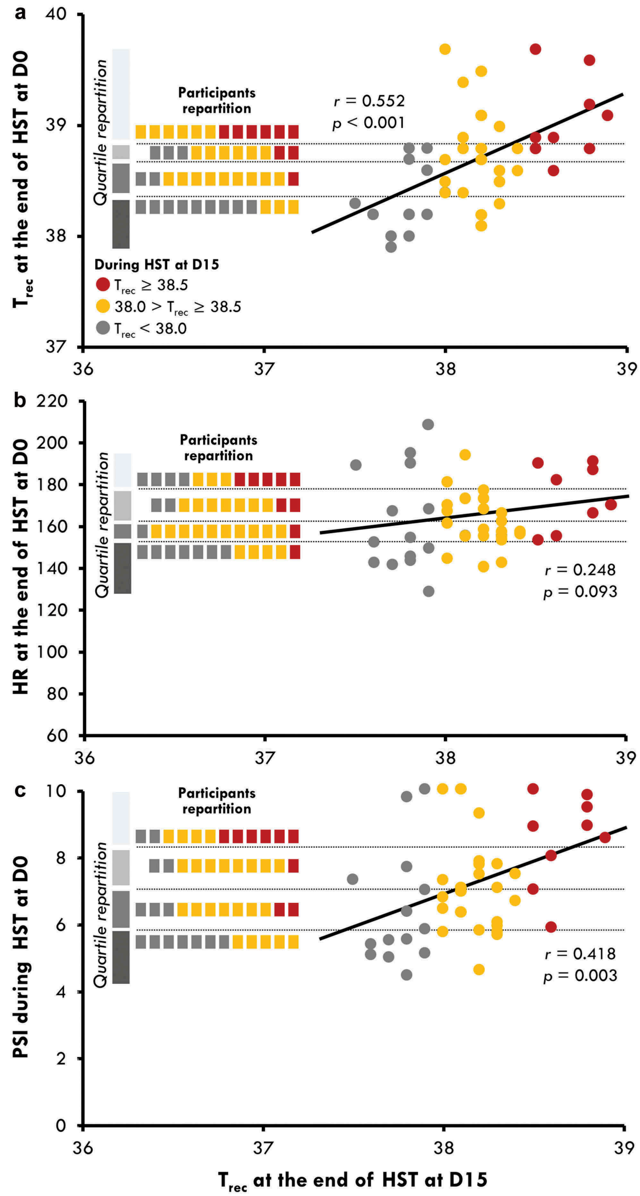

Figure 5. Correlations between the main basal markers (T_{rec} (a) and HR (b) at the end of the HST and PSI (c)) and T_{rec} at the end of the HST at D15. Participants that were still "at risk" at D15 are highlighted by the colors (red circles for T_{rec} above 38.5 and yellow circles for T_{rec} between 38.0 and 38.5°C). Participants were divided into quartiles based on the basal response at D0. The repartition of participants "at risk" was unequal for T_{rec} and PSI (p = 0.011 for both). Circles may sometimes be superimposed.

(Figure 2), as already observed in previous studies [1–3,5–7]. The challenge is to understand why some individuals tolerate exercise in the heat well and thus require only a few days to maximize their responses while others are less heat tolerant and need more than two weeks to completely acclimatize to the heat. Despite the obvious deleterious effects of heat on performance [31], very few athletes compete in a heat-acclimated state [8]. Moreover, even if athletes wish to arrive weeks earlier to the site of competition to benefit from heat acclimatization, the environmental conditions prior to the event may sometimes be less harsher than during the competition [32]. Thus, the identification of predictors determining the ideal amount of time required to reach complete adaptation would be a significant advancement in the field of physical training. It would allow optimization of heat acclimation through individualization and likely increase compliance to heat acclimation programs.

Predictability of the adaptive responses during heat acclimatization

General characteristics (age, height, BM, BSA, body mass index) and fitness level failed to predict any marker of the adaptive response to heat acclimatization. However, the sample was relatively homogenous, since all were young (less than 35 years old), very active male soldiers but not competing athletes. The range of differences in these general characteristics was therefore possibly too narrow to facilitate the identification of pertinent marker(s). Differences in heat acclimation based on a specific characteristic are usually observed between very distinct groups: 70 vs 25 years old [9], 18 vs 33% body fat mass [10], or 60.7 vs 35.6 ml.min^{-1}.kg^{-1} of VO_{2max} [12]. A recent study of Zurawlew et al. [33] elegantly demonstrated this issue. Adaptive responses after a short heat acclimation program using post-exercise hot water immersion were assessed in a heterogeneous sample (VO_{2max}: 45–80 ml.min^{-1}.kg^{-1}). Although the improvements in HR during the HST were highly different between the extremes (< 50 and > 65 ml.min^{-1}.kg^{-1}), the range of responses was still very large for the intermediate individuals (between 50 and 65 ml.min^{-1}.kg^{-1}, such as for the vast majority of the participants of the present study), suggesting that individual characteristics (biometrics and fitness level) cannot predict the adaptive responses at the end of heat acclimation in a homogenous sample. Corbett et al. [2] also did not find any associations with markers of adaptive responses in a homogenous sample of young trained males, as in the present study. Although this study and that of Corbett et al. [2] suggest that age, morphology, and fitness level do not predict adaptive responses, further studies with wider and more heterogeneous samples are required to confirm this assertion. Nonetheless, these criteria are not relevant in the present military population who share very similar physical characteristics.

The initial responses to the HST appear to provide more predictive information on the adaptive response to heat acclimation/acclimatization. The correlation analyses led to a number of observations: 1) individuals with lower heat tolerance during the initial HST tended to benefit from larger adaptive responses, 2) individuals with lower heat tolerance during the initial HST tended to remain less tolerant during the final HST, and 3) a classical marker of heat tolerance (*e.g.* T_{rec}) poorly correlated with the adaptive response of another marker of heat tolerance (*e.g.* HR). The first observation is in agreement with the historic studies of Dreosti [14–16] in which he prescribed the number of heat acclimation sessions (4, 7, or 14 days) to applicants before their starting work in the gold mines, based on their initial heat tolerance status (absolute T_{rec} after a 60-min HTT; < 37.8, between 37.8 and 38.9°C, and > 38.9°C, respectively). Although this procedure was not supported by controlled assessments of the level of heat acclimatization after the realization of the prescribed sessions, Dreosti was the first and last to propose a medical/scientific approach to successfully (in terms of the death rate) protect workers exposed to very harsh conditions. The present results largely support those of his study: heat intolerant individuals are likely to present larger adaptive responses. Corbett et al. [2] also reported similar results, with initial values in body temperature and HR during the HST correlating well with the magnitude of the reductions in these markers following heat acclimation.

Interestingly, the least tolerant individuals before heat acclimatization were still the least tolerant at the end of heat acclimatization. Thus, 14 days of heat acclimatization in the context of this study was not sufficient for them to catch up with the more tolerant participants. It is therefore very likely that, for some individuals, the traditional and systematic period of 15 days [34,35] is not always sufficient to reach complete acclimatization. In addition, recent data have shown that heat acclimatization in a military context may not be complete after 15 days, as improvements are still observed during a HTT after 23 days [36]. Conversely, the most tolerant participants could be ready for operation before this period. Regardless of the amplitude of the adaptive responses during heat acclimatization, the basal thermotolerance is critical.

Predictability of the residual risk during acclimatization

T_{rec} above 38.5°C is considered to be a threshold value to differentiate between heat-intolerant and heat-tolerant individuals [28,29]. This cut off value has been developed for highly-controlled laboratory tests and may be poorly adapted for field exercises. Indeed, a greater tolerance to high core temperature has been observed in field than laboratory tests [37]. However, given the absence of values adapted for the field, we used the 38.5°C threshold to identify participants still "at risk" at the end of heat acclimatization. Based on the interpretation of the correlations, we explored whether basal markers of thermoregulation were able to discriminate participants who would remain "at risk" despite 14 days of acclimatization. The aim was to propose a simple method to identify soldiers that could be rapidly sent on missions and others who would require a longer period of acclimatization before being operational. This method was strongly influenced by the work of Dreosti [14–16]. The first approach consisted of separating the participants into two groups: one "at risk" and the other "safe", based on T_{rec} values at D15. We then performed a ROC analysis to know whether the main basal markers of the HST at D0 were sufficiently sensitive and specific to predict the participants still "at risk" at D15. The risk scores based on the AUC were ranked as good (0.8–0.9) only for T_{rec} at the end of the HST, and the PSI (Figure 4). The second complementary step consisted of using the correlation between these basal markers and T_{rec} at the end of the HST at D15 (Figure 5). Most of the participants "at risk" were in the upper quartile (*i.e.* the least tolerant) of T_{rec} and PSI. Removal of these individuals with a high chance of still being "at risk" at the end of acclimatization resulted in 3 of 47 participants (6%) being wrongly predicted to be "safe". Removal of the 50% least tolerant particpants resulted in only one (2%) false negative for T_{rec} and two (4%) for PSI. The results of this study show that the predictibility of the adaptive response and the detection of the participants still "at risk" based on basal thermoregulatory responses can still be improved and that further studies are required to identify finer and/or complementory predictors. Nonetheless, a simple and convenient method was proposed that may help to identify two subgroups: those who are at high risk to be insufficiently acclimatized after 14 days and to face heat illness during demanding operational missions and those who will not benefit much from heat acclimatization, given that their high basal level of heat tolerance. This method necessarly requires experimental confirmation and there is a small risk of falsely identifying individuals not "at risk". However, in a military context with time pressure and operations in hot conditions, its application may increase operational performance and thus reduce the risk of jeopardizing missions.

Limitations

Heat acclimation/acclimatization protocols are characterized by large variability in the experimental design [35]. Thus, the HST (intensity, duration, ergometer, temperature, and relative humidity) and heat acclimation period (duration, nature, intensity and duration of physical activities, temperature, and relative humidity) are often specific to a particular study and transpositions and comparisons of results are necessarily limited. This study is no exception and the results should be considered in light of its specific design: i.e. 14-d acclimatization performed in an operational military context.

The duration between the two HSTs (14 days) was based on consistent observations [34,35] that adaptation reaches its upper limit at this time. Although it would have been possible to observe different individual responses over shorter or longer periods, it was necessary to select a referential duration of heat acclimatization. Moreover, it has been recently observed that 14 days are not sufficient to reach maximal adaptation in a military heat acclimatization protocol [36,38], indicating that we would have observed a myriad of individual responses (from partial to complete), allowing the identification of predictors of the adaptive responses.

A major point in using the HST is the importance of normalizing metabolic heat production. On an ergocycle, relative intensities in $W.kg^{-1}$ rather than the same absolute intensity in W was proposed, as the latter induced similar heat production and increased T_{rec} in a heterogeneous sample in terms of body morphology [39,40]. Thus, fixing intensities in W or percentage of VO_{2max} or power at VO_{2max} may induce a large range of responses that may be unrelated to the level of heat tolerance but rather to different levels of heat production. Thermoregulation on a treadmill is less well documented. Although some have reported that body size may influence T_{rec} at the same walking speed [41,42], others found no difference between women with low and high body masses [43]. A relative intensity (50% of speed at VO_{2max}) not normalized to BM was used because, as stated by Corbett et al. [2] "it is typically assumed to be of little relevance for within–participant design, so long as the same external work-rates are used post-heat acclimation". However, Corbett et al. [2] found a correlation between the magnitude of decrease in T_{rec} after heat acclimation and the absolute basal heat production during the HST, suggesting that the design of the HST may influence the subsequent adaptive responses. This is currently very hypothetical and is yet to be confirmed, especially for running.

Conclusions

High variability of both thermo-physiological responses during a basal HST and the adaptive responses during heat acclimatization even though the participants were relatively homogenous was observed. The main adaptive responses did not correlate with individual characteristics and fitness level but rather with certain responses in the basal HST. Thorough analysis showed that the least tolerant participants at baseline were those that exhibited the greatest adaptation during heat acclimatization. Nevertheless, they remained less tolerant than the participants with a high basal level of heat tolerance, showing that the improvements were insufficient to achieve heat tolerance after 14 days of heat acclimatization. T_{rec} at the end of the HST at D0 may be a simple and convenient parameter to differentiate between individuals who will remain "at risk", despite 14 days of acclimatization, and should be retained and those that could be mobilized more rapidly after arrival to a site characterized by a hot environment. These observations are yet to be demonstrated in other contexts, such as classical heat-acclimation protocols. Thus, although the HST used in this study performed before acclimatization was able to partially predict the level of heat tolerance after 14 days of heat acclimatization, its ability to predict the incidence of heat illness needs to be demonstrated in further studies.

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Author contributions

AM, PETD, and KC designed the study and performed the research. KC and JS conducted the statistical analyses and drafted the initial manuscript. KC designed the figures and wrote the first draft of the manuscript. All authors reviewed and revised the manuscript, approved the final manuscript as submitted, and agree to be accountable for all aspects of the work.

Disclosure statement

No potential conflict of interest was reported by the authors.

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